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CHAPTER 21

VERY LOW FREQUENCY RADIO WAVE PROPAGATION AT HIGH LATITUDES

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ABSTRACT

Diurnal, seasonal and yearly variations of the normal 16 *kc/s signal strength from the Rugby (GBR) transmitter* ($\phi = 52{\cdot}4°N$; $\lambda = 1{\cdot}2°W$) *have been studied on the basis of data accumulated during approximately five years of continuous recording (September* 1958 *to May* 1963) *at Kiruna Geophysical Observatory* ($\phi = 67{\cdot}8°N$; $\lambda = 20{\cdot}4°E$). *The principal experimental findings are as follows:*

(1) *For the first two years of observation the average monthly signal strength was of much greater intensity during the day than at night. More than* 90 *per cent of all individual days during this period show this behaviour. Between August* 1961 *and December* 1962 *the average ratio between the nocturnal and daytime signal level was approximately one, but this ratio varied considerably from month to month. Since January* 1963, *the average monthly signal strength has shown a markedly higher signal level during the night-time than during daylight hours. This holds true for about* 80 *per cent of all individual days during the months of January to May,* 1963.

(2) *The best propagation conditions for v.l.f. communications between Rugby and Kiruna have been found during the summer months, and the lowest signal strength has always been found during the winter months. But while the average summer-time signal strength was approximately twice as high as in winter for the years* 1959 *and* 1960, *the corresponding figure for* 1962 *is only about* 1·2.

(3) *A maximum of the* 16 *kc/s signal strength was observed in* 1960 *about two years after the sunspot curve reached its maximum. The propagation conditions deteriorated substantially in* 1962 *and* 1963, *the average signal level being less than two-thirds of that for the years* 1959 *and* 1960.

The observed day–night variation of the 16 *kc/s signal strength is discussed in terms of the mode theory of propagation, in a first-order approximation. For the case when the night-time signal level is lower than the daytime level (as for the years* 1958 *to* 1961), *an increase of apparent reflection heights from* 70 *km at day to* 80–85 *km at night can explain the observation. An increase in reflection heights of say* 5–10 *km both during night and day, may explain the observations obtained during the more quiet ionospheric conditions in* 1961 *to* 1963; *namely that the night-time signal strength was of greater intensity than that during the daytime. The reception of* 16 *kc/s Rugby transmissions at Uppsala* ($\phi = 59{\cdot}8°N$; $\lambda = 17{\cdot}6°E$) *supports this conclusion.*

The marked decrease in ionospheric absorption for the periods when the night-time level of the 16 *kc/s signal strength exceeded the daytime level, can be understood if the region, where the main part of the ionospheric absorption, as well as the reflection of very low frequency waves takes place, was some kilometres higher than during the remainder of the observation period.*

From these results it seems reasonable to conclude that the height of the D-region is lowest during years of high solar activity and highest during years of more quiet ionospheric conditions. The average increase in reflection heights from 1959 *to* 1963 *may be of the order of* 5–10 *km.*

1. INTRODUCTION

CONTINUOUS field strength measurements of the 16 kc/s transmissions from Rugby (GBR) (geographic coordinates 52·4°N; 1·2°W) have been made at Kiruna Geophysical Observatory (geographic coordinates 67·8°N; 20·4°E) since September 1958. The map in Fig. 1 shows the geographic situation of the transmitter and receiver as well as the distance from the transmitter.

During the observation period of almost 5 years, no instance of signal disappearance was noted at Kiruna although several major ionospheric disturbances occurred and interrupted long distance radio communication over most of the frequency range used for that purpose.

The reader is referred to the paper by Egeland (1961) for a description of the methods of measurement and the analysis of data. Here it needs only to be mentioned that the 16 kc/s signal strength has been read off at each quarter of the hour.

The observational data presented in this paper have mainly been studied with respect to the normal diurnal, seasonal, and yearly variation of the received field strength. The observed day–night variation of the 16 kc/s signal strength will be discussed in relation to the variation of apparent reflection heights. Furthermore, the variation in reflection heights of v.l.f. radio waves will be compared with the variation of ionospheric absorption during the same period.

2. TIME VARIATIONS OF THE NORMAL PROPAGATION CONDITIONS FOR THE 16 KC/S TRANSMISSIONS BETWEEN RUGBY AND KIRUNA

2.1. *Diurnal and Day to Night Variation*

The signal characteristics of the 16 kc/s waves show a high degree of variability over a 24-hr period, though this variability is relatively consistent. Curves showing the normal diurnal variation of v.l.f. signal strength contain the well-known minima at the approximate times of sunrise and sunset. The characteristics of the sunrise and sunset minima have been described by e.g. Bailey and Harper (1936), and Lauter and Schmelovsky (1958). This effect is thought to be a result of reciprocal interference of waves reflected simultaneously from the "day layer" and the "night layer" (cf. e.g. Bracewell and Bain, 1952; Lauter and Schmelovsky, 1958).

An interesting feature of long range radio wave propagation at high latitudes was observed during the 2-month periods of midnight sun at Kiruna. The sunrise and sunset minima so overlap during these months that only one significant minimum is recorded approximately at local midnight. This effect is demonstrated by the average diurnal variation curves for each month in 1962 which are plotted in Fig. 2a. The curves give the average median values for each hour. On some days the sunrise minimum was found to be somewhat stronger than that at sunset, but on other days the contrary was the case. The average monthly field strengths at sunrise and sunset are approximately equal for all months. At lower latitudes and for shorter

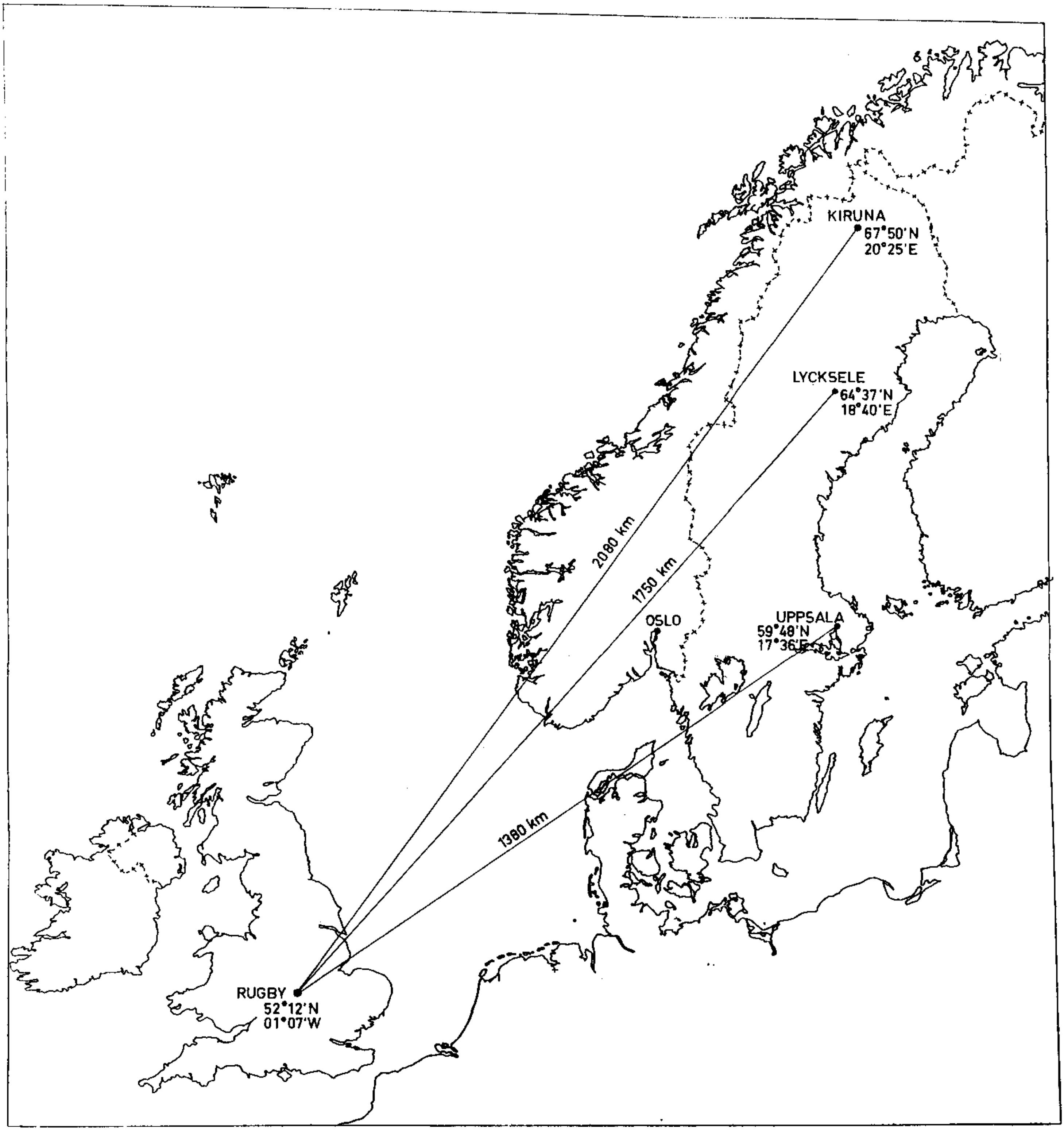

Fig. 1. Map of Northern Europe showing the locations of the transmitter and receiver stations.

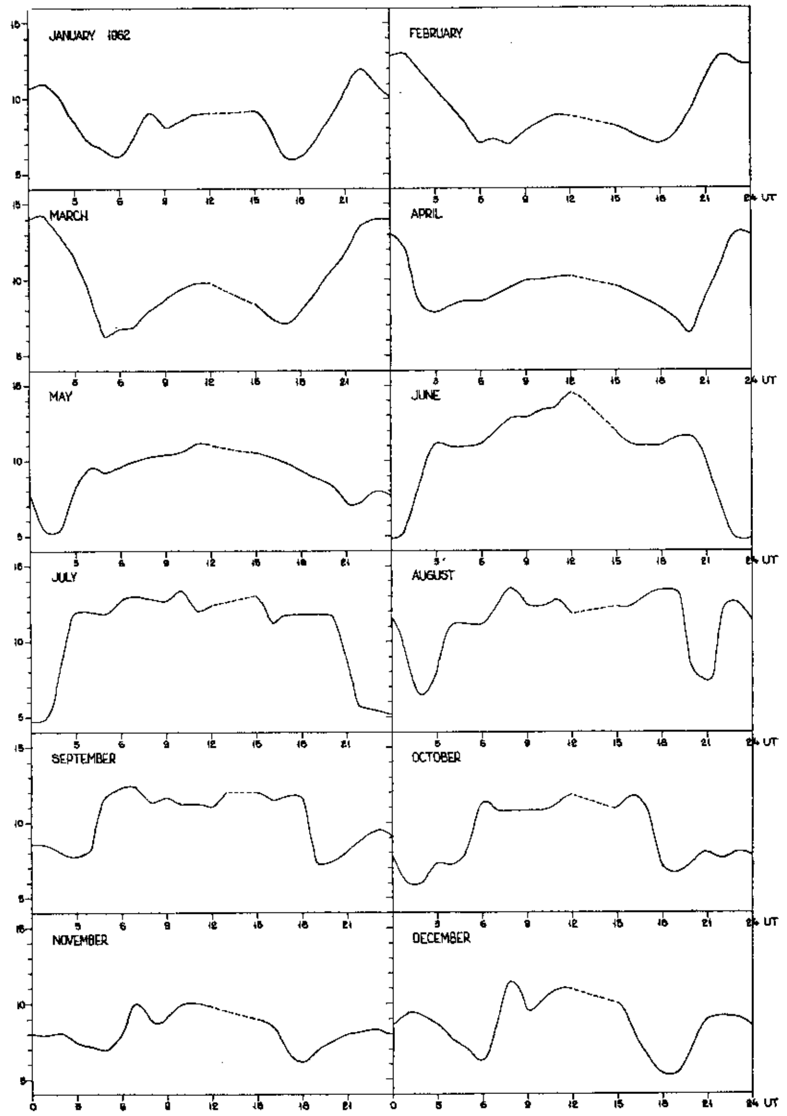

Fig. 2a. *The average diurnal variation curves of the* 16 *kc/s signal strength for the period* 1 *January* 1962 *to* 31 *December* 1962.

distances, the sunrise minimum has been found to be most pronounced for 16 kc/s radio waves (Kitchen *et al.*, 1953).

The intensity of the night-time signals fluctuates throughout the night, especially during the winter months, while the daytime values are highly constant for up to 18 hr daily during the summer months. The daylight intensity is considerably more variable in the winter than in the summer, the daylight signal lasting only about 7 hr in December. The normal diurnal variation curves for the amplitude of the 16 kc/s signals were often found to show slight maxima, with an average duration of about 20 min, at the start of the constant day level. A corresponding increase in signal strength was frequently observed a short time before the start of the nocturnal amplitude

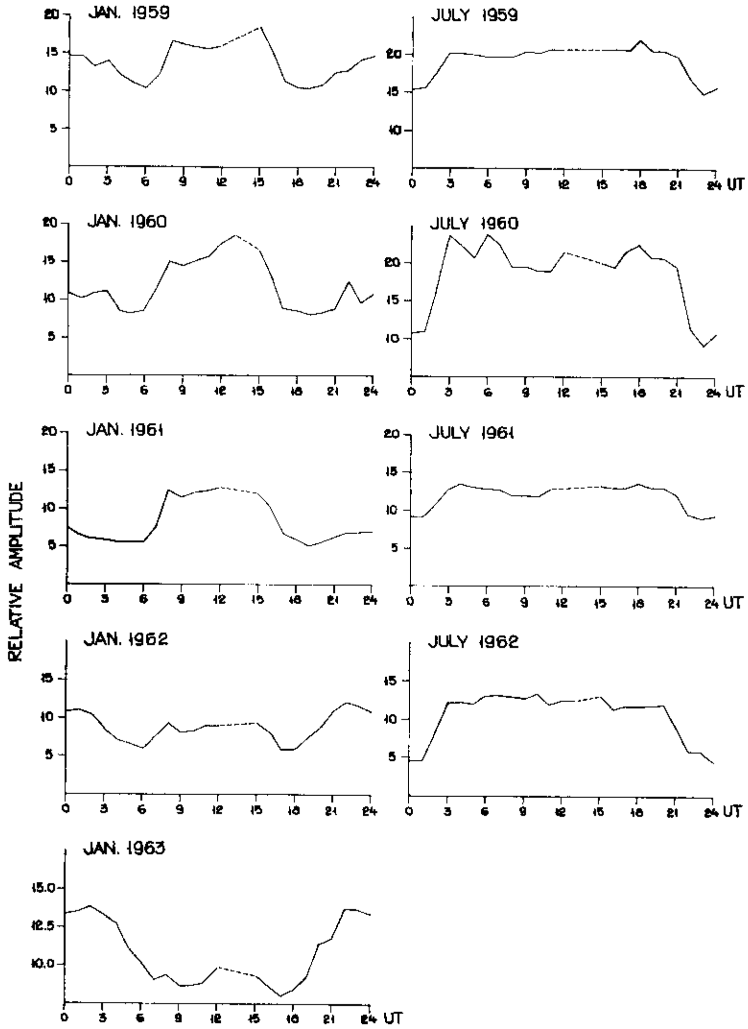

Fig. 2b. *The average diurnal variation of the* 16 *kc/s signal strength for the months January and July,* 1959 *to* 1963.

decrease. These maxima almost disappear in the averaged monthly curves (cf. Fig. 2a). The difference in the diurnal variation during the observation period is demonstrated in Fig. 2b by the average curves for January and July each year.

The average daytime and night-time signal strength of 16 kc/s transmissions from Rugby for each month during the observation period is shown in Fig. 3. As mentioned above, the sunset and sunrise minima overlap during the summer months, so it is not possible to obtain any significant nocturnal value for these months. The double dotted curves in Fig. 3 represent the signal strength around midnight. As Fig. 3 clearly indicates, the average monthly signal strength at Kiruna between September 1958 and February 1961 was of much greater intensity during the day than at night.

The curve for August 1961 shows, for the first time during the observation period, that the average night-time signal strength was of greater intensity than that during the day. For September, October and November 1961 (cf. Fig. 3)

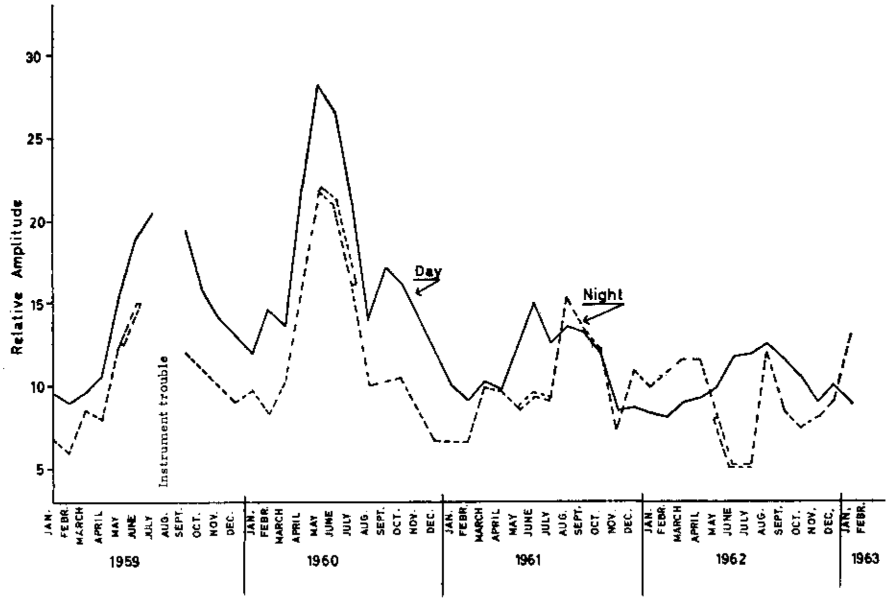

Fig. 3. The seasonal and yearly variation of recorded field strength. The average monthly intensity is plotted for the daylight and night hours separately.

the signal strengths during day and night were approximately equal, while for the period December 1961 to April 1962 the night-time level was again of greater intensity than that during the day. Also for the months January–May 1963, the recorded field strength clearly indicates that the propagation conditions for 16 kc/s transmissions from Rugby were markedly better during the night-time than during the day.

The day to night variation of the signal strength for each individual day during the observation period from January 1959 to April 1963 has been studied. Table 1 shows the number of days in each month when the night-time signal strength level exceeded the daytime level and vice versa. For reasons given above, the data for the summer months have not been included in these statistics. The last column in the table gives the average percentage of days during the respective years, when the night-time signal strength exceeded the daytime level.

In 1959 and 1960, less than 10 per cent of the days showed maximum

Table 1

Month	*Jan.* *No. of days*		*Febr.* *No. of days*		*March* *No. of days*		*April* *No. of days*		*Aug.* *No. of days*		*Sept.* *No. of days*		*Oct.* *No. of days*		*Nov.* *No. of days*		*Dec.* *No. of days*		*Average % of days with max. signal strength during the the night-time*
Years	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	
1959	3	16	0	18	3	24	3	23	no	obs.	2	26	2	26	1	29	1	28	7·9
1960	4	27	1	17	7	18	2	24	3	18	2	25	3	24	0	28	0	28	9·5
1961	5	25	5	22	9	21	12	15	16	15	14	10	16	14	6	18	18	13	39·8
1962	25	6	21	7	27	4	13	9	17	11	8	21	6	23	8	20	8	23	51·6
1963	14	6	18	10	26	3	25	2											79·9

Columns A = number of days when night-time level exceeds daytime level
Columns B = number of days when daytime level exceeds night-time level

signal strength during the night-time hours. In 1962, the signal strength for more than 50 per cent of the days was of greater intensity during the night than during the day, and in 1963 about 80 per cent of all days clearly indicate that the night-time signal level exceeded that during the daylight hours. Furthermore, the difference between night-time and daytime levels is most marked in 1963.

Although the average monthly propagation condition for the 16 kc/s transmission between Rugby and Kiruna varies considerably between daytime and night-time during the observation period, the following conclusions can be drawn:

(1) During years of high average ionospheric disturbance (i.e. 1958–1960) the daytime signal strength was of markedly higher intensity than the night-time value.

(2) In the first six months of 1961 the difference between the propagation conditions during day and night was smaller than in 1958–1960, but also in this period the daytime level exceeds that recorded during the night-time.

(3) During the rather quiet ionospheric period between August 1961 and May 1963 the average ratio between the night and daytime field strength was approximately one (cf. Fig. 3). For two periods, viz. December 1961 to May 1962, and January to May 1963, the propagation conditions for 16 kc/s radio waves between Rugby and Kiruna were much better during the night than during the daytime.

2.2. *Seasonal and Yearly Variation of the Observed Signal Strength*

The seasonal and yearly variations of the observed signal strength from January 1959 to March 1963 are shown in Fig. 4 along with the magnetic Appindices and the sunspot numbers for the same period. The average intensity for the 24-hr period is plotted for each month.

The highest intensities, or the best propagation conditions, have always been observed during summer months (May, June and July), while the lowest signal strengths have been found during winter months (November–February). A somewhat abrupt seasonal change in the v.l.f. propagation conditions occurred in March or April, and a corresponding reversed change in August or September (cf. Fig. 4). While the average signal strength was approximately twice as high in summer as in winter, for the years 1959 and 1960, the corresponding figure for 1962 was only 1·2.

Concerning the annual variation, Fig. 4 clearly indicates that the 16 kc/s signal strength for the transmissions between Rugby and Kiruna reached its maximum in 1960. The propagation conditions deteriorated substantially after 1960, the average signal level being less than two-thirds of that for the years 1959 and 1960. Furthermore, the greatest decrease in signal strength has been found for the summer periods. Also, in the winter periods, the field strength is lower in 1962 and 1963 than in 1959 and 1960, but the overall decrease during the period 1958 to 1963 is much slower than for the summer months.

By comparing the three curves in Fig. 4, it is found that the best propagation conditions for 16 kc/s radio waves between Rugby and Kiruna existed in 1960; the same year in which the magnetic disturbance curves reached its

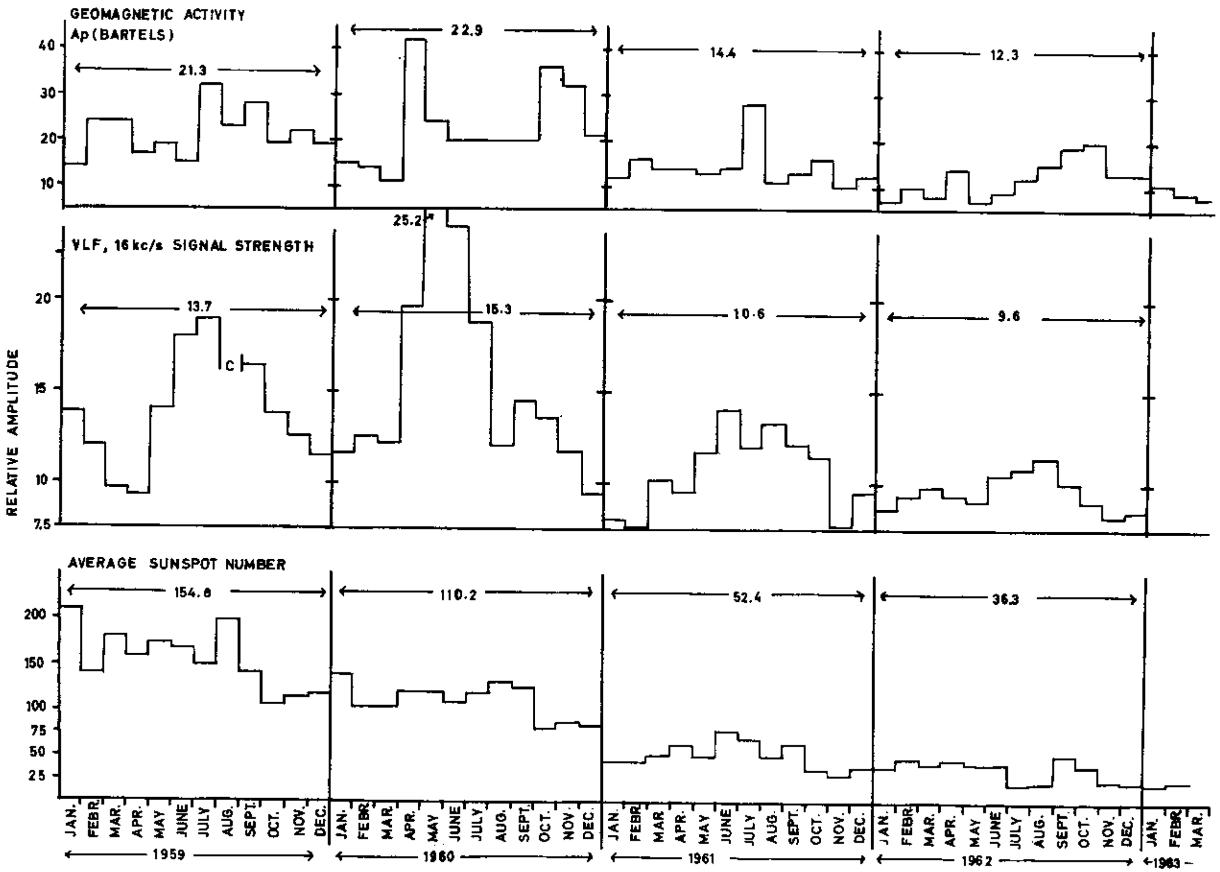
GEOMAGNETIC ACTIVITY
Ap (BARTELS)
21.3
22.9
14.4
12.3
VLF, 16 kc/s SIGNAL STRENGTH
RELATIVE AMPLITUDE
25.2
13.7
15.3
10.6
9.6
C
AVERAGE SUNSPOT NUMBER
154.8
110.2
52.4
36.3
1959
1960
1961
1962
1963

Fig. 4.

maximum, which is approximately two years after the last sunspot maximum. A time lag of about two years, referred to the last sunspot maximum, has been observed at Kiruna for both visual and radio-aurora (cf. Egeland, 1962). For further details concerning the influence of solar disturbances on the 16 kc/s propagation between Rugby and Kiruna, cf. the paper by Egeland *et al.* (1961).

3. INTERPRETATION IN TERMS OF A FIRST-ORDER MODE THEORY

3.1. *Variations of Averaged Apparent Reflection Heights*

As has been mentioned in the preceding sections, the day–night variations of signal level were such that during most of the period of recordings the night level was smaller than the day level. (Here the signal strengths used represent values which have been averaged over the respective month.) For a few months, however, the contrary was true, that is, the recorded amplitudes were higher by night than by day.

The following is an attempt to interpret this behaviour qualitatively and to draw some approximate conclusions. As is well known, the propagation of v.l.f.-waves can, in general, best be described in terms of mode theory; i.e. earth and ionosphere are considered as the boundaries of a waveguide. Extensive theoretical investigations have been made on the properties of such a waveguide (see e.g. Wait, 1962). Now the distance from Rugby to Kiruna (2100 km) is such that, for the frequency in question (16 kc/s) it is not possible to make any useful simplification in the general solutions. At shorter distances from the transmitter than say 1500 km, simple principles of geometrical optics can be applied, while at distances beyond 5000 km or so, the higher modes are highly damped so that a one-mode theory can be used in this range. Kiruna is situated in the transition region, which makes the application of theory somewhat more complicated.

We shall confine ourselves to mode theory in a first-order approximation, that is we make assumptions which are quite well validated during daytime but probably not at night. These include a sharply bounded isotropic ionosphere with a reflection coefficient of unit magnitude and a phase angle of 180 degrees. The earth is taken as flat and infinitely conducting. The latter assumption yields, according to Volland (1959), an error not in excess of 5 per cent.

Under these assumptions curves of relative mode sum versus distance ρ have been calculated by Frisius (1962) for the Rugby frequency with h as a parameter. Examples are shown in Fig. 5. From these curves a diagram of relative amplitude versus height for Kiruna has been deduced (see Fig. 6a).

In terms of these results the difference between day and night signal strengths can be interpreted for the case when the night level is lower than the day level, as an increase of apparent reflection heights from 70 km to 80–85 km, say. This is in good agreement with what has been reported in the literature, viz. that at this very low frequency the normal ionosphere reflects the waves at relatively low heights—about 70 km in daytime and 85 km at night (cf. e.g. Kitchen *et al.*, 1953; Crombie *et al.*, 1958; Jean *et al.*, 1960; Volland, 1959; Wait, 1959).

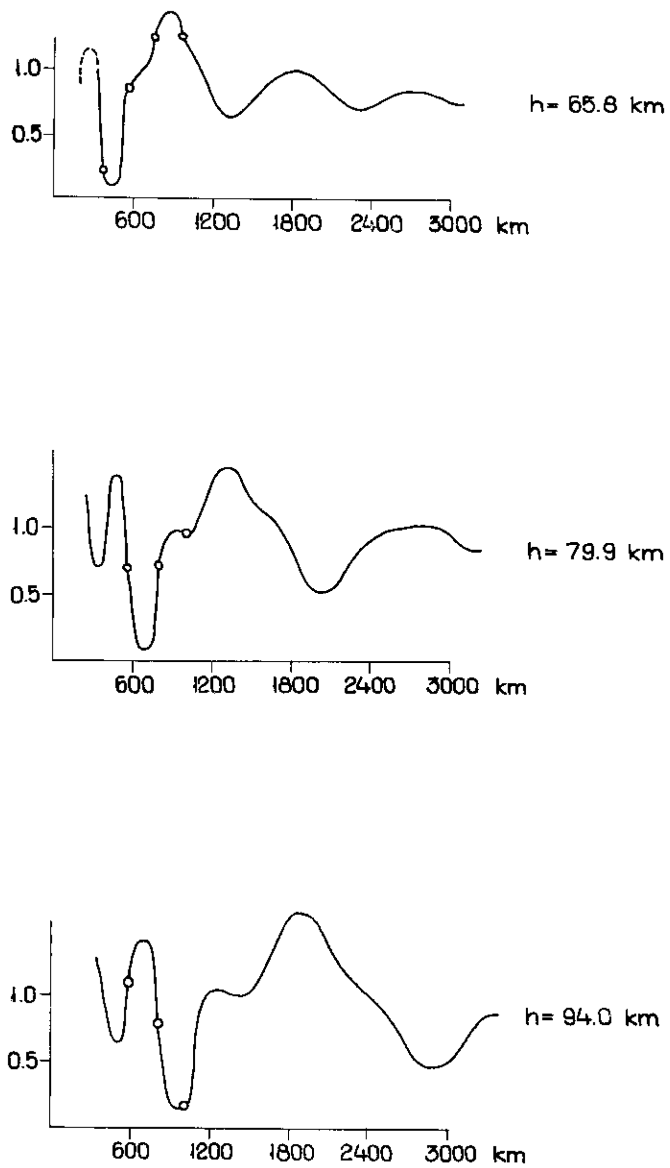

Fig. 5. *Curves of relative mode sum versus distance from the transmitter for* 16 *kc/s receptions with apparent reflection height as a parameter. After Frisius* (1962).

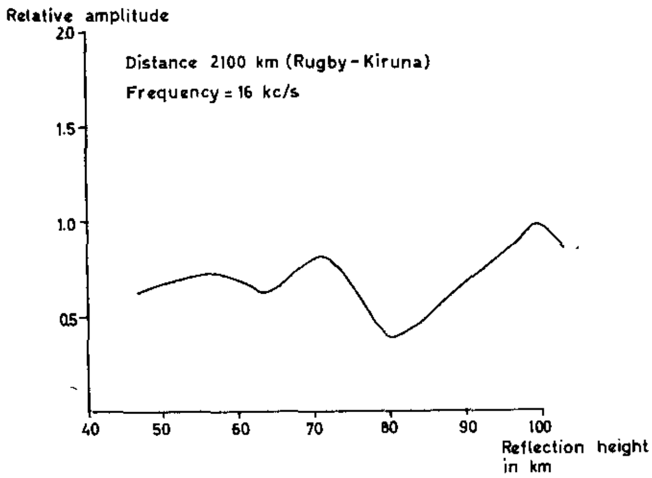

Fig. 6a. *Curve of relative amplitude versus reflection height for Kiruna.*

The other case (night level higher than day level) would then mean that the reflection process, both at night and day took place at greater heights (perhaps 5–10 km) than for the previous case. Of course, one must always keep in mind that the assumptions used are crude, and give only qualitative results. In order to obtain a check on this interpretation the Rugby signal recordings from Uppsala ($\phi = 59{\cdot}8°$N; $\lambda = 17{\cdot}6°$E) have been analysed for some months, including both cases of day–night relationship at Kiruna. They did not exhibit any corresponding change in behaviour, which could be expected from plotting a similar curve to Fig. 6a for Uppsala with $\rho = 1380$ km (cf. Fig. 6b).

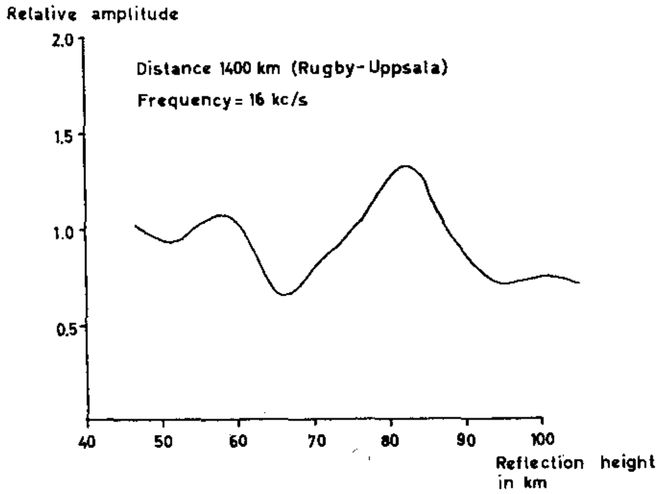

Fig. 6b. *Curve of relative amplitude versus reflection height for Uppsala.*

So one arrives at the conclusion that during the periods August 1961, December 1960 to April 1962 and January to May 1963, the mean value of the apparent reflection height was greater than during the rest of the observation period. If this is really true, it seems reasonable that this should correspond to a reduction of nondeviative ionospheric absorption. Unfortunately, no riometer recordings are available at approximately midpath

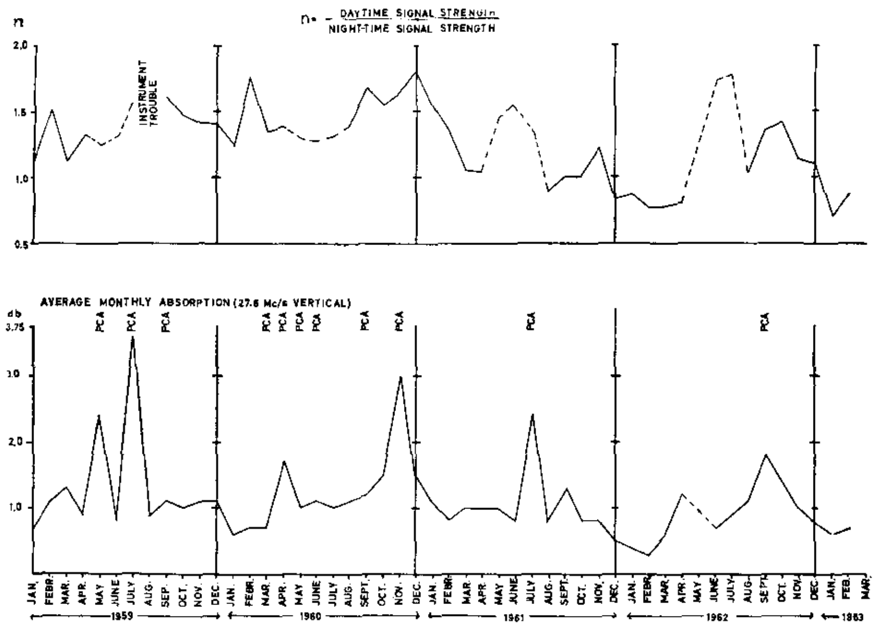

Fig. 7.

between Rugby and Kiruna. So the riometer recordings at Kiruna for 27·6 Mc/s were taken, and they indeed show the expected behaviour. Figure 7 shows the average monthly absorption for Kiruna together with the ratio between day and night levels of v.l.f.-signal amplitude during the reported period. The only exception from the otherwise good agreement with what has been said above, viz. April 1962, is not so significant, since it may be interpreted as being caused by a phenomenon whose range in latitude did not reach Kiruna.

3.2. *Special Examples of* 16 *kc/s Signal Strength and Ionospheric Absorption Recordings*

The considerations of the preceding sections have referred mainly to average values of signal strength and variation of apparent reflection heights, taken over monthly periods. In the following, the individual daily behaviour of the 16 kc/s signal strength, as well as its correlation with ionospheric absorption, will be discussed in some more detail for three typical periods.

The averaged hourly signal strength at Kiruna, for these periods, is plotted in Fig. 8, together with the maximum ionospheric absorption at 27·6 Mc/s (in dB) at Kiruna, during each hour, for the same days. For each of the three periods, the 16 kc/s data show the change from a night-time maximum on one day to a maximum level during the daylight hours on the following day. By comparing the individual days for the three periods, it is found that during these night–day variations, the changes in night-time propagation conditions are much more marked than during the daylight hours.

The correlation between increases in ionospheric absorption and decreases in the 16 kc/s signal strength (especially during the night) is well demonstrated in the curves. Furthermore, during the periods of high and longlasting riometer absorption, the daytime level exceeded the night-time level.

These observations can be explained from the simple mode theory if, as mentioned in Section 3.1, the region where radio-wave absorption, as well as the reflection of very low frequency waves take place, were some kilometres lower during disturbed ionospheric conditions than during the more quiet periods. The decrease in absorption accompanying the increase in the height of the mainly absorbing region fits well into the above picture. According to what has been said above, the way of visualizing the reflection mechanism of v.l.f.-waves by means of a first order approximation provides quite good agreement with experiment. It should be mentioned that it has proved useful in explaining sudden changes in v.l.f. field strength caused by Soviet nuclear explosions, observed at Kiruna and Uppsala (Riedler *et al.*, 1963).

To get better insight into the problem and the theory which should be used, an additional receiver has recently been set up in Lycksele ($\phi = 64{\cdot}6°$N; $\lambda = 18{\cdot}7°$E), between Uppsala and Kiruna. It should allow the changes in apparent reflection height to be followed more accurately.

4. SUMMARY AND CONCLUSIONS

Ionospheric propagation of radio waves at 16 kc/s between Rugby, England, and Kiruna, Sweden, a distance of about 2100 km, has been investigated during approximately 5 years of continuous recording.

The gradual change from a daytime maximum in signal strength during 1959 and 1960 to a night-time maximum during 1962 and 1963, has been well demonstrated. Furthermore, the best propagation conditions for this 16 kc/s communication were observed in 1960, about two years after the sunspot curve reached its maximum. The signal strength decreased substantially in 1962 and 1963, the average signal level being less than two-thirds of that for the years 1959 and 1960.

By comparing these observations with geomagnetic conditions and the ionospheric absorption during the same period, the following conclusions may be drawn:

(1) The propagation conditions for 16 kc/s radio waves, between Rugby and Kiruna, and the geomagnetic activity exhibit roughly the same annual variation. Both curves reached their maximum in 1960, while in 1962 and 1963 the average 16 kc/s signal strength and the geomagnetic activity were markedly lower compared to the years 1959 and 1960.

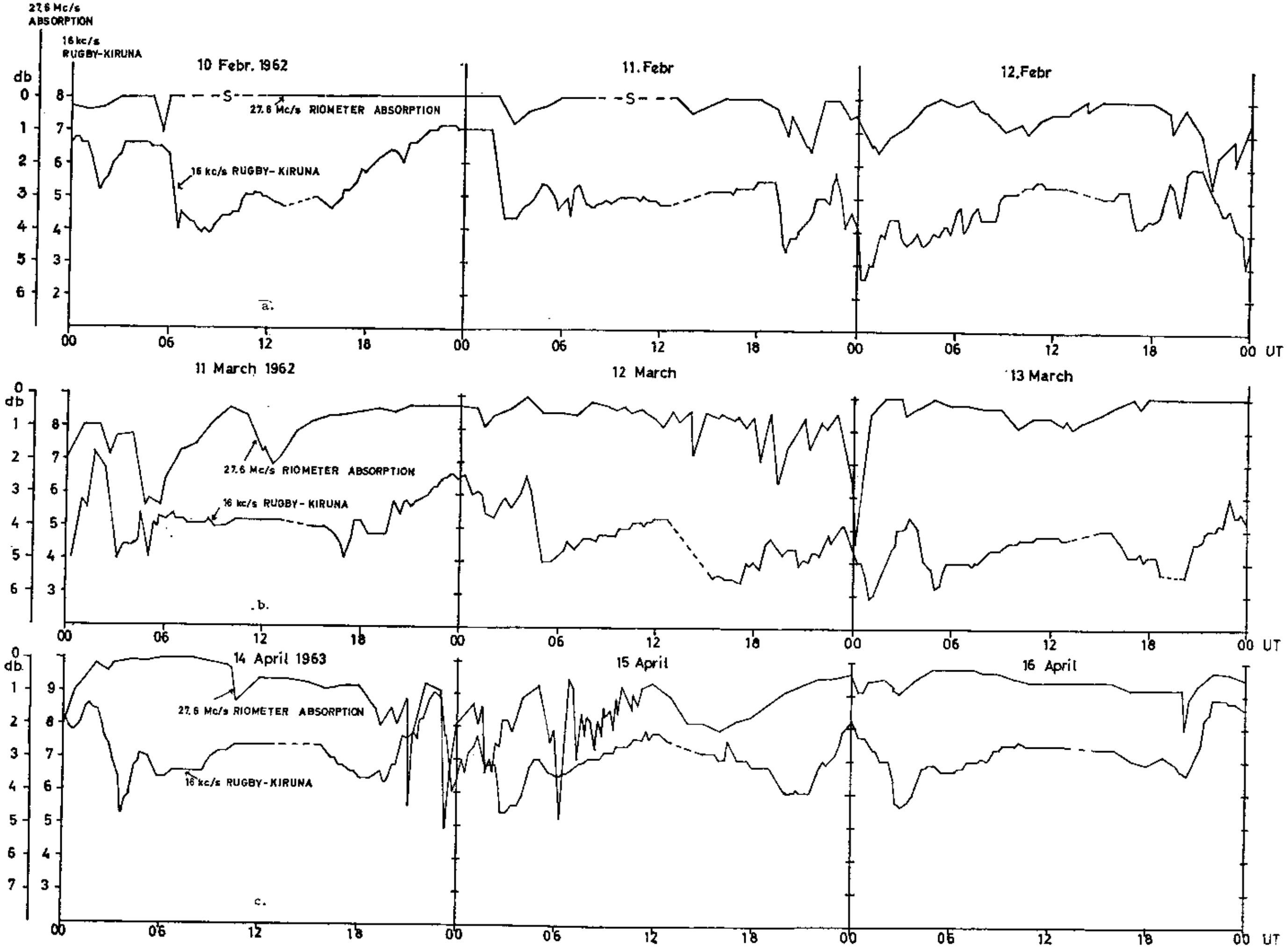

Fig. 8. Day to day variation curves of 16 kc/s signal strength (relative amplitude) and 27.6 Mc/s cosmic noise ...

(2) The periods during which a night-time maximum occurred in the 16 kc/s signal strength coincided with the quiet geomagnetic years. In 1959 and 1960, during the years of maximum geomagnetic and ionospheric disturbance, the 16 kc/s daytime signal level was markedly higher than that during the night. The pronounced decrease in ionospheric absorption for all periods when the night-time level of the 16 kc/s signal strength exceeded the daytime level, supports the model of a varying apparent reflection height, according to a first-order mode theory.

From these results it seems reasonable to conclude that the average height of the *D*-region is lowest during highly disturbed periods, and highest during very quiet ionospheric conditions. When the change in the day to night variation of the 16 kc/s signal strength is discussed in relation to a mode theory of propagation, for a first-order approximation, the assumption of gradual increase of apparent reflection height of 5 to 10 km both during day and night, in 1962 and 1963 as compared to the year 1959 and 1960, explains the observations.

The average height of the *D*-region, during both day and night, seems to vary with the sunspot cycle. Furthermore, the v.l.f. data together with a simple mode theory allow the conclusion that the average increase in reflection height from 1959 to 1963 may be of the order of 5–10 km.

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